

EVALUATION OF n + 208Pb CROSS SECTIONS FOR THE ENERGY  
RANGE 1.0E-11 to 150 MeV

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This evaluation provides a complete representation of the nuclear data needed for transport, damage, heating, radioactivity, and shielding applications over the incident neutron energy range from 1.0E-11 to 150 MeV. The discussion here is divided into the region below and above 30 MeV.

INCIDENT NEUTRON ENERGIES < 30 MeV

Below 30 MeV the evaluation is based completely on a new evaluation by Young and Chadwick that will be submitted to ENDF/B for a future release of ENDF/B-VI. The only change made to the Young-Chadwick evaluation was to remove the covariance data file (MF=3), which had been carried over from an earlier ENDF/B-VI evaluation.

INCIDENT NEUTRON ENERGIES > 30 MeV

The evaluation above 20 MeV utilizes MF=6, MT=5 to represent all reaction data. Production cross sections and emission spectra are given for neutrons, protons, deuterons, tritons, alpha particles, gamma rays, and all residual nuclides produced ( $A>5$ ) in the reaction chains. To summarize, the ENDF sections with non-zero data above  $E_n = 20$  MeV are:

MF=3 MT= 1 Total Cross Section  
MT= 2 Elastic Scattering Cross Section  
MT= 3 Nonelastic Cross Section  
MT= 5 Sum of Binary (n,n') and (n,x) Reactions

MF=4 MT= 2 Elastic Angular Distributions

MF=6 MT= 5 Production Cross Sections and Energy-Angle Distributions for Emission Neutrons, Protons, Deuterons, and Alphas; and Angle-Integrated Spectra for Gamma Rays and Residual Nuclei That Are Stable Against Particle Emission

The evaluation is based on nuclear model calculations that have been benchmarked to experimental data, especially for n + Pb and p + Pb208 reactions (Ch96a). We use the GNASH code system (Yo92), which utilizes Hauser-Feshbach statistical, preequilibrium and direct-reaction theories. Coupled-channel and spherical optical model calculations are used to obtain particle transmission coefficients for the Hauser-Feshbach calculations, as well as for the elastic neutron angular distributions.

Cross sections and spectra for producing individual residual nuclei are included for reactions that exceed a cross section of approximately 1 nb at any energy. The energy-angle-correlations for all outgoing particles are based on Kalbach systematics (Ka88).

A model was developed to calculate the energy distributions of all recoil nuclei in the GNASH calculations (Ch96b). The recoil

energy distributions are represented in the laboratory system in MT=5, MF=6, and are given as isotropic in the lab system. Note that all other data in MT=5, MF=6 are given in the center-of-mass system. This method of representation requires a modification of the original ENDF-6 format.

Preequilibrium corrections were performed in the course of the GNASH calculations using the exciton model of Kalbach (Ka77, Ka85), validated by comparison with calculations using Feshbach, Kerman, Koonin (FKK) theory [Ch93]. Discrete level data from nuclear data sheets were matched to continuum level densities using the formulation of Ignatyuk (Ig75) and pairing and shell parameters from the Cook (Co67) analysis. Neutron and charged-particle transmission coefficients were obtained from the optical potentials, as discussed below. Gamma-ray transmission coefficients were calculated using the Kopecky-Uhl model (Ko90).

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#### REFERENCES

[Ch93]. M.B. Chadwick and P.G. Young, "Feshbach-Kerman-Koonin Analysis of  $^{93}\text{Nb}$  Reactions:  $\text{P} \rightarrow \text{Q}$  Transitions and Reduced Importance of Multistep Compound Emission," Phys. Rev. C 47, 2255 (1993).

[Ch96a]. M. B. Chadwick and P. G. Young, "GNASH Calculations of  $n, p + 206, 207, 208\text{Pb}$  and Benchmarking of Results" in APT PROGRESS REPORT: 1 July - 1 August 1996, internal Los Alamos National Laboratory memo T-2-96/MS-40, 7 Aug. 1996 from R.E. MacFarlane to L. Waters.

[Ch96b]. M. B. Chadwick, P. G. Young, R. E. MacFarlane, and A. J. Koning, "High-Energy Nuclear Data Libraries for Accelerator-Driven Technologies: Calculational Method for Heavy Recoils," Proc. of 2nd Int. Conf. on Accelerator Driven Transmutation Technology and Applications, Kalmar, Sweden, 3-7 June 1996.

[Co67]. J.L. Cook, H. Ferguson, and A.R. Musgrave, "Nuclear Level Densities in Intermediate and Heavy Nuclei," Aust.J.Phys. 20, 477 (1967).

[Ha92]. G. M. Hale, P. G. Young, M. B. Chadwick, and Z.-P. Chen, "New Evaluations of Neutron Cross Sections for  $^{14}\text{N}$  and  $^{16}\text{O}$ , Proc. Int. Conf. on Nuclear Data for Science and Technology, Jflich, Germany, 13-17 May 1991 (LA-UR-91-1516), 126 [Ed. S. M. Qaim, Springer-Verlag, Germany (1992)], p. 921.

[Ig75]. A.V. Ignatyuk, G.N. Smirenkin, and A.S. Tishin, "Phenomenological Description of the Energy Dependence of the Level Density Parameter," Sov. J. Nucl. Phys. 21, 255 (1975).

[Ka77]. C. Kalbach, "The Griffin Model, Complex Particles and Direct Nuclear Reactions," Z.Phys.A 283, 401 (1977).

[Ka85]. C. Kalbach, "PRECO-D2: Program for Calculating Preequilibrium and Direct Reaction Double Differential Cross Sections," Los Alamos National Laboratory report LA-10248-MS (1985).

[Ka88]. C. Kalbach, "Systematics of Continuum Angular

Distributions: Extensions to Higher Energies," Phys.Rev.C 37, 2350 (1988); see also C. Kalbach and F. M. Mann, "Phenomenology of Continuum Angular Distributions. I. Systematics and Parameterization," Phys.Rev.C 23, 112 (1981).

[Ko90]. J. Kopecky and M. Uhl, "Test of Gamma-Ray Strength Functions in Nuclear Reaction Model Calculations," Phys.Rev.C 42, 1941 (1990).

[Yo92]. P.G. Young, E.D. Arthur, and M.B. Chadwick, "Comprehensive Nuclear Model Calculations: Introduction to the Theory and Use of the GNASH Code," LA-12343-MS (1992).

82208 = TARGET 1000Z+A (if A=0 then elemental)

1 = PROJECTILE 1000Z+A

Nonelastic, elastic, and Production cross sections for A&lt;5 projectiles in barns:

Energy	nonelas	elastic	neutron	proton	deuteron	triton	helium3	alpha	gamma
3.000E+01	2.558E+00	2.569E+00	7.414E+00	6.930E-02	1.261E-02	1.661E-03	0.000E+00	1.906E-03	1.089E+01
3.500E+01	2.541E+00	2.109E+00	7.920E+00	1.340E-01	1.797E-02	2.191E-03	0.000E+00	2.485E-03	1.089E+01
4.000E+01	2.502E+00	1.858E+00	8.272E+00	2.133E-01	2.283E-02	2.541E-03	0.000E+00	2.935E-03	1.121E+01
4.500E+01	2.433E+00	1.821E+00	8.582E+00	2.760E-01	2.528E-02	2.768E-03	0.000E+00	3.361E-03	1.155E+01
5.000E+01	2.383E+00	1.907E+00	8.873E+00	3.368E-01	2.748E-02	2.921E-03	0.000E+00	3.813E-03	1.144E+01
5.500E+01	2.323E+00	2.074E+00	9.080E+00	3.911E-01	2.909E-02	3.023E-03	0.000E+00	4.290E-03	1.068E+01
6.000E+01	2.274E+00	2.208E+00	9.275E+00	4.423E-01	2.984E-02	3.101E-03	0.000E+00	4.842E-03	1.032E+01
6.500E+01	2.200E+00	2.402E+00	9.314E+00	4.835E-01	3.072E-02	3.142E-03	0.000E+00	5.377E-03	1.008E+01
7.000E+01	2.125E+00	2.573E+00	9.201E+00	5.171E-01	3.133E-02	3.183E-03	0.000E+00	5.979E-03	8.440E+00
7.500E+01	2.050E+00	2.700E+00	9.140E+00	5.464E-01	3.185E-02	3.230E-03	0.000E+00	6.626E-03	8.256E+00
8.000E+01	1.976E+00	2.830E+00	9.173E+00	5.647E-01	3.184E-02	3.266E-03	0.000E+00	7.526E-03	8.001E+00
8.500E+01	1.923E+00	2.883E+00	9.245E+00	5.870E-01	3.196E-02	3.336E-03	0.000E+00	8.589E-03	7.935E+00
9.000E+01	1.893E+00	2.853E+00	9.425E+00	6.111E-01	3.224E-02	3.476E-03	0.000E+00	9.955E-03	8.016E+00
9.500E+01	1.855E+00	2.808E+00	9.537E+00	6.299E-01	3.229E-02	3.646E-03	0.000E+00	1.144E-02	8.048E+00
1.000E+02	1.822E+00	2.768E+00	9.636E+00	6.492E-01	3.237E-02	3.867E-03	0.000E+00	1.307E-02	7.984E+00
1.100E+02	1.780E+00	2.594E+00	9.927E+00	6.887E-01	3.248E-02	4.498E-03	0.000E+00	1.701E-02	7.823E+00
1.200E+02	1.742E+00	2.416E+00	1.018E+01	7.227E-01	3.223E-02	5.365E-03	0.000E+00	2.172E-02	7.610E+00
1.300E+02	1.704E+00	2.249E+00	1.039E+01	7.497E-01	3.183E-02	6.492E-03	0.000E+00	2.711E-02	7.226E+00
1.400E+02	1.666E+00	2.072E+00	1.051E+01	7.747E-01	3.135E-02	7.767E-03	0.000E+00	3.328E-02	7.048E+00
1.500E+02	1.630E+00	1.928E+00	1.063E+01	7.954E-01	3.085E-02	9.253E-03	0.000E+00	4.504E-02	7.010E+00

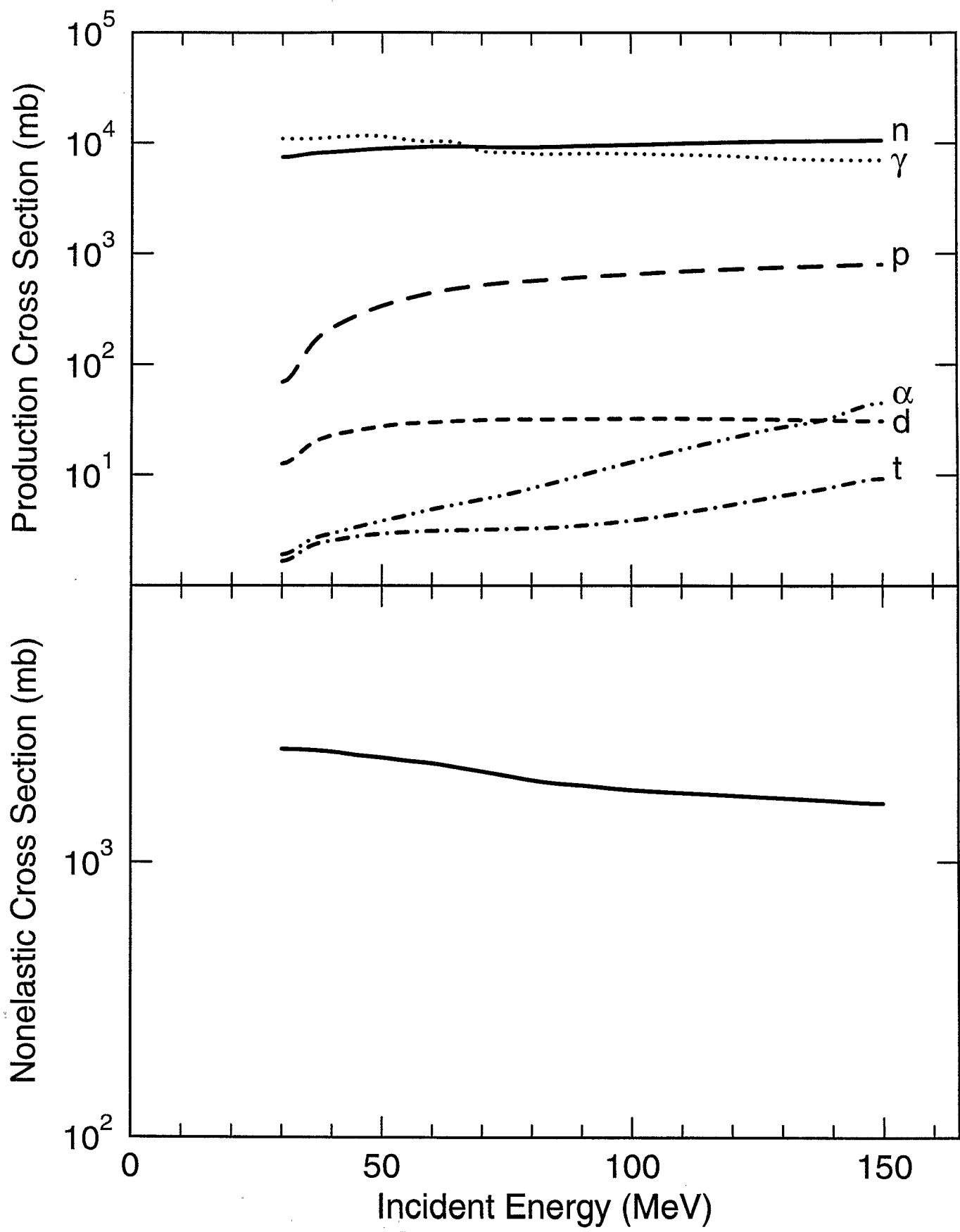
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1 = PROJECTILE 1000Z+A

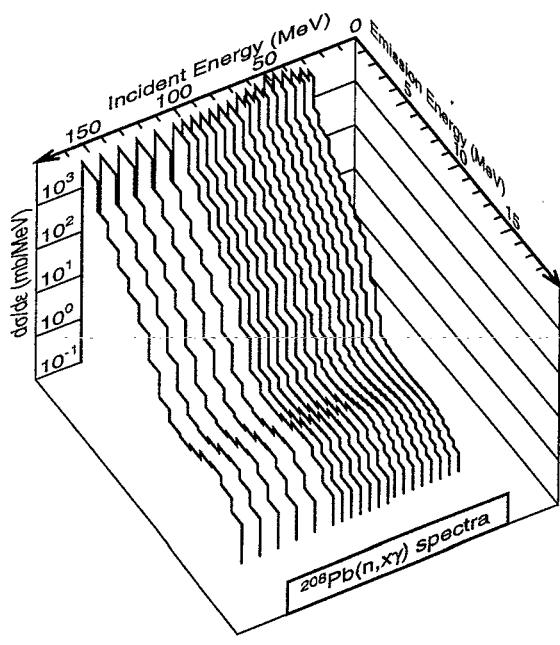
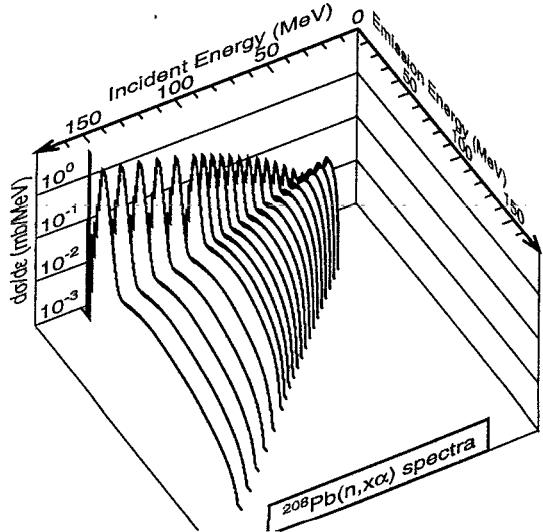
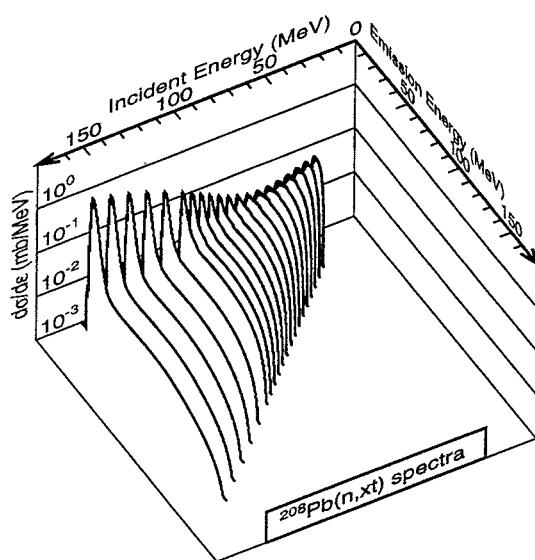
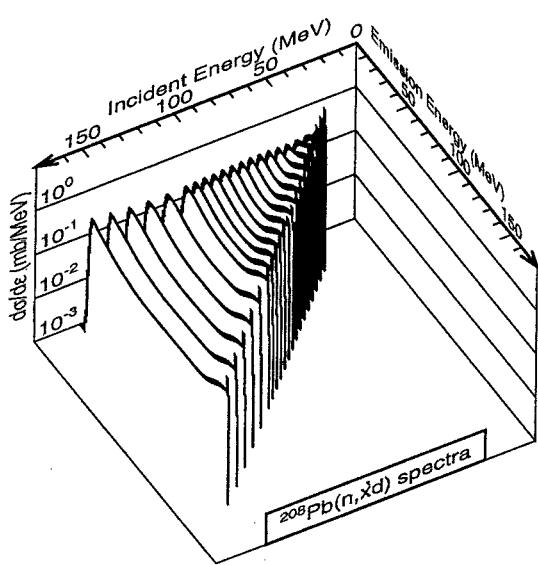
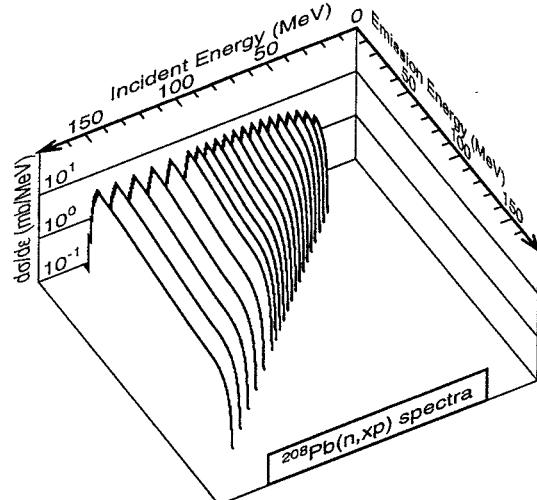
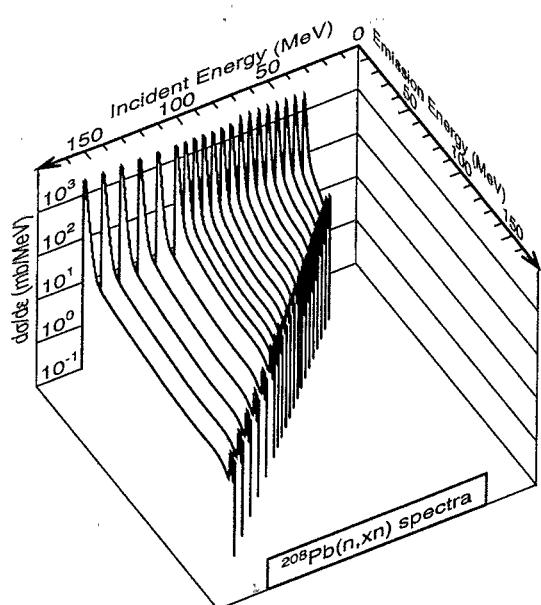
Kerma coefficients in units of f.Gy.m^2:

Energy	proton	deuteron	triton	helium3	alpha	non-rec	elas-rec	TOTAL
3.000E+01	5.173E-02	1.088E-02	1.235E-03	0.000E+00	2.286E-03	1.983E-02	2.345E-03	8.831E-02
3.500E+01	1.128E-01	1.800E-02	1.857E-03	0.000E+00	3.220E-03	2.221E-02	2.316E-03	1.604E-01
4.000E+01	2.005E-01	2.613E-02	2.403E-03	0.000E+00	4.072E-03	2.426E-02	2.257E-03	2.597E-01
4.500E+01	2.855E-01	3.234E-02	2.884E-03	0.000E+00	4.898E-03	2.581E-02	2.490E-03	3.539E-01
5.000E+01	3.789E-01	3.882E-02	3.314E-03	0.000E+00	5.756E-03	2.730E-02	2.671E-03	4.567E-01
5.500E+01	4.734E-01	4.481E-02	3.698E-03	0.000E+00	6.619E-03	2.833E-02	2.796E-03	5.596E-01
6.000E+01	5.716E-01	4.913E-02	4.047E-03	0.000E+00	7.549E-03	2.928E-02	2.774E-03	6.644E-01
6.500E+01	6.629E-01	5.421E-02	4.342E-03	0.000E+00	8.409E-03	2.966E-02	2.764E-03	7.623E-01
7.000E+01	7.493E-01	5.895E-02	4.620E-03	0.000E+00	9.287E-03	3.003E-02	2.567E-03	8.547E-01
7.500E+01	8.342E-01	6.361E-02	4.891E-03	0.000E+00	1.016E-02	2.991E-02	2.360E-03	9.452E-01
8.000E+01	9.067E-01	6.723E-02	5.080E-03	0.000E+00	1.119E-02	2.977E-02	2.214E-03	1.022E+00
8.500E+01	9.888E-01	7.106E-02	5.273E-03	0.000E+00	1.238E-02	2.987E-02	2.056E-03	1.109E+00
9.000E+01	1.078E+00	7.523E-02	5.505E-03	0.000E+00	1.386E-02	3.029E-02	1.885E-03	1.205E+00
9.500E+01	1.161E+00	7.884E-02	5.720E-03	0.000E+00	1.542E-02	3.045E-02	1.742E-03	1.294E+00
1.000E+02	1.249E+00	8.244E-02	5.954E-03	0.000E+00	1.711E-02	3.056E-02	1.630E-03	1.386E+00
1.100E+02	1.435E+00	8.914E-02	6.474E-03	0.000E+00	2.119E-02	3.105E-02	1.448E-03	1.584E+00
1.200E+02	1.620E+00	9.415E-02	7.033E-03	0.000E+00	2.598E-02	3.134E-02	1.307E-03	1.780E+00
1.300E+02	1.798E+00	9.801E-02	7.704E-03	0.000E+00	3.143E-02	3.230E-02	1.199E-03	1.968E+00
1.400E+02	1.977E+00	1.010E-01	8.430E-03	0.000E+00	3.733E-02	3.378E-02	1.103E-03	2.158E+00
1.500E+02	2.149E+00	1.034E-01	9.252E-03	0.000E+00	4.547E-02	3.523E-02	1.035E-03	2.343E+00

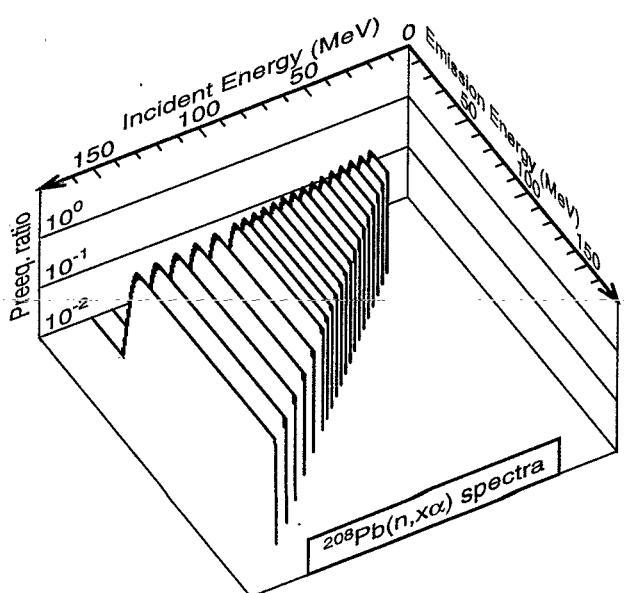
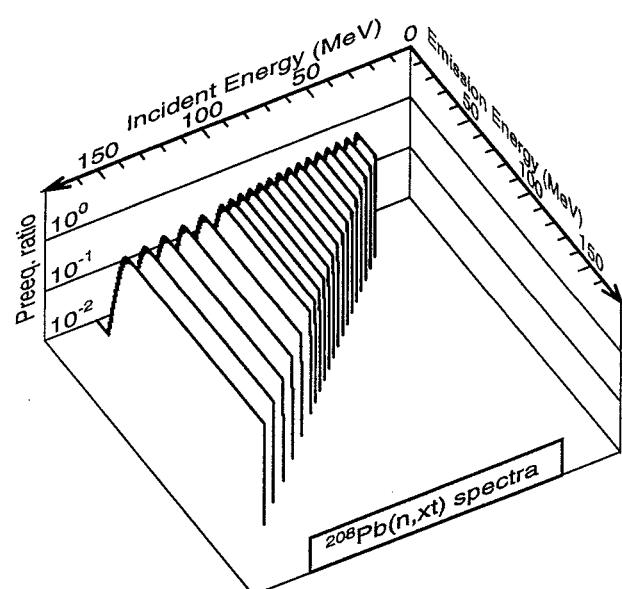
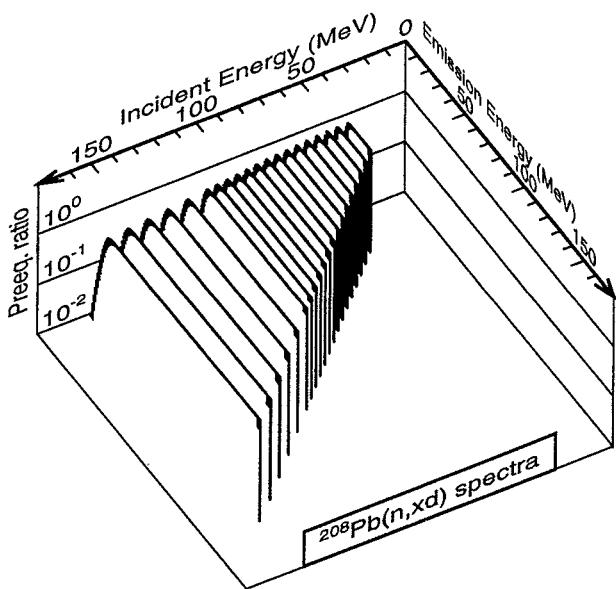
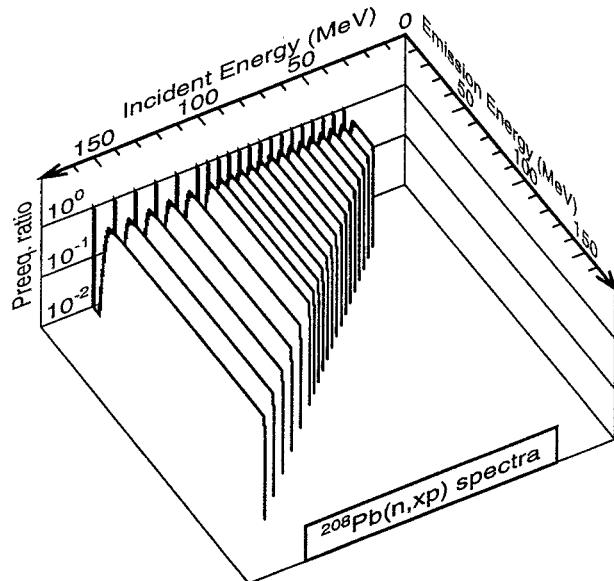
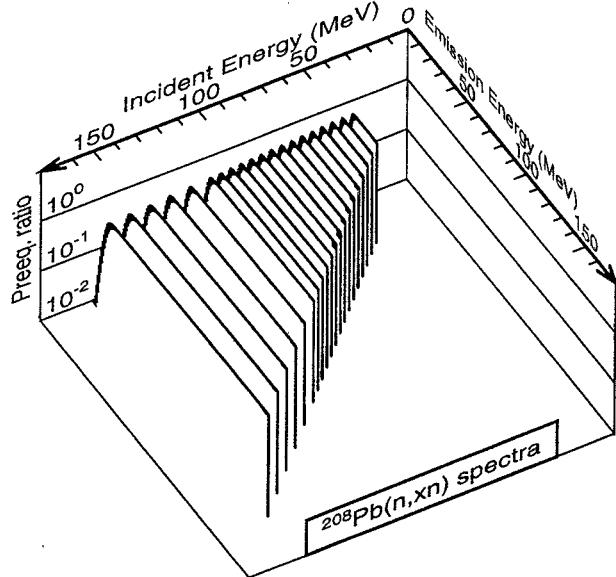
$n + {}^{208}\text{Pb}$  nonelastic and production cross sections



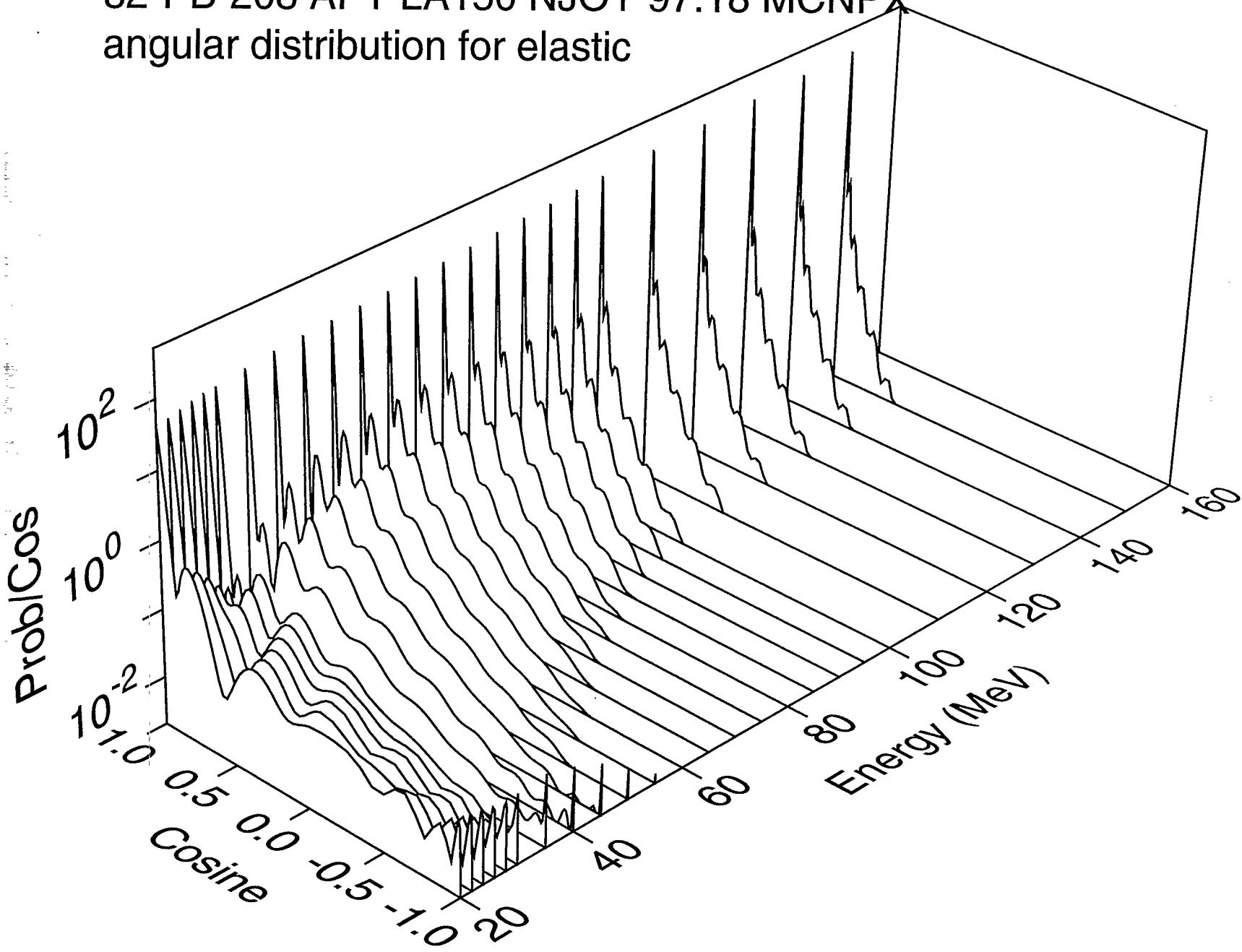
# $n + {}^{208}\text{Pb}$ angle-integrated emission spectra



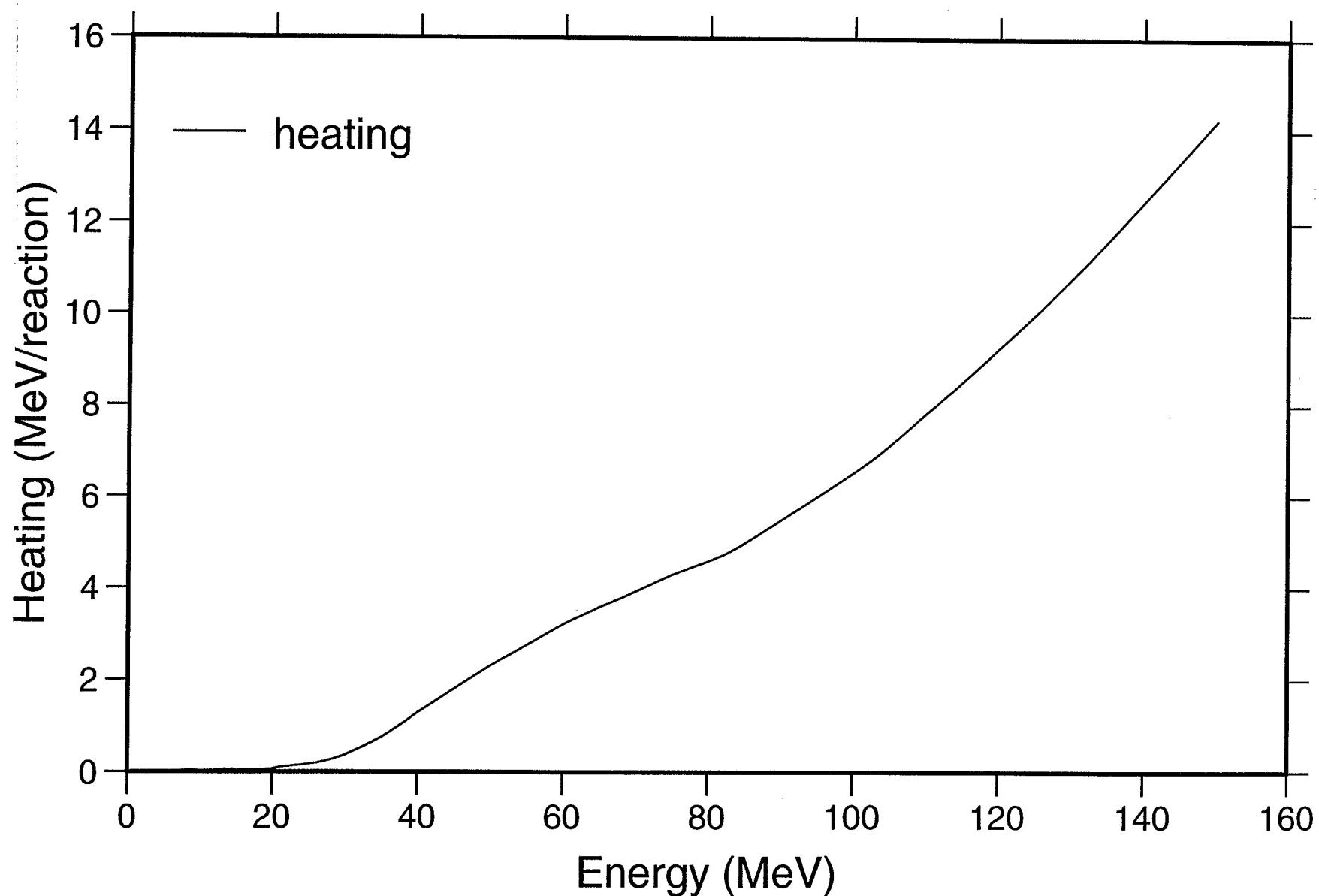
# $n + ^{208}\text{Pb}$ Kalbach preequilibrium ratios



82-PB-208 APT LA150 NJOY 97.18 MCNPX  
angular distribution for elastic



82-PB-208 APT LA150 NJOY 97.18 MCNPX  
Heating



82-PB-208 APT LA150 NJOY 97.18 MCNPX  
Damage

